



HAL
open science

First principles modeling of fast electron physics

Y Peysson, D Mazon, J F Artaud, A Ekedahl, J Hillairet, A Jardin, K Kroll, J Bielecki, D Dworak, M Scholz, et al.

► **To cite this version:**

Y Peysson, D Mazon, J F Artaud, A Ekedahl, J Hillairet, et al.. First principles modeling of fast electron physics. ICFRD 2020 - International conference on diagnostics for fusion reactors, ICPC (International Center Piero Caldirola), Sep 2021, Varenne, Italy. cea-03467619

HAL Id: cea-03467619

<https://cea.hal.science/cea-03467619>

Submitted on 6 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DE LA RECHERCHE À L'INDUSTRIE



www.cea.fr

First principles modeling of fast electron physics

**Y. Peysson^{1*}, D. Mazon¹, J. F. Artaud¹, A. Ekedahl¹,
J. Hillairet¹, A. Jardin², K. Kroll², J. Bielecki²,
D. Dworak², M. Scholz², J. Decker³
and WEST Team⁺**

¹CEA/IRFM, F-13108, Saint-Paul-lez-Durance, France

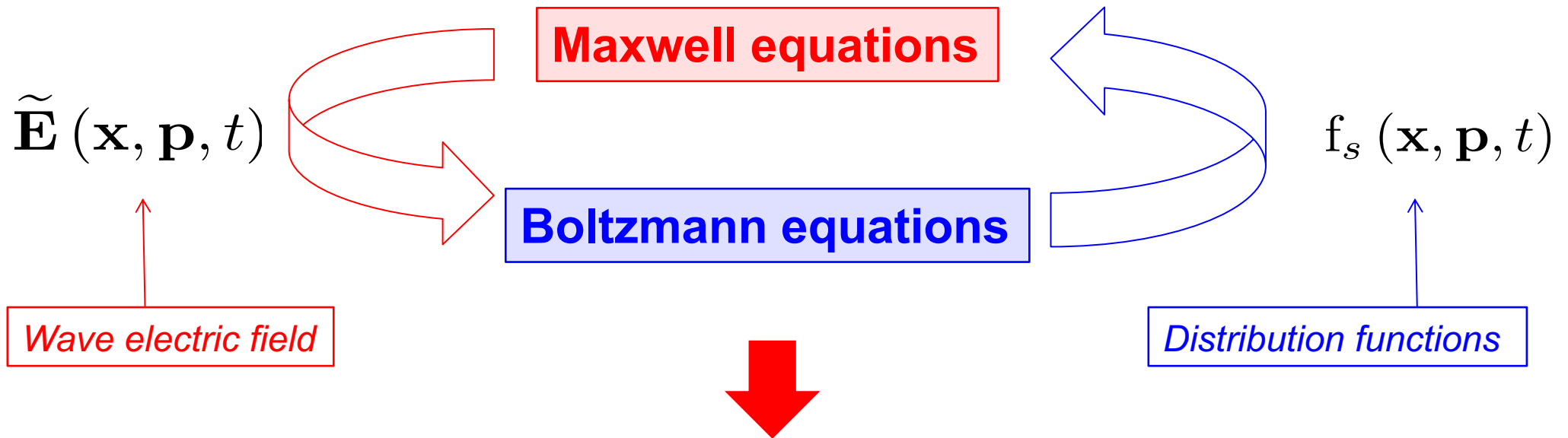
²Institute of Nuclear Physics, Polish Academy of Sciences, Kraków,
Poland

³EPFL, Swiss Plasma Center, CH-1015 Lausanne, Switzerland

* yves.peysson@cea.fr

+ <http://west.cea.fr/WESTteam>

- First principles modeling
- LUKE : a versatile tool for modeling fast electron physics
- Towards large scale quantitative simulations with LUKE
- SLUKE : a new framework for automatic LUKE modeling
- Conclusion and prospects



$\tilde{\mathbf{E}}(\mathbf{x}, \mathbf{p}, t)$

$f_s(\mathbf{x}, \mathbf{p}, t)$

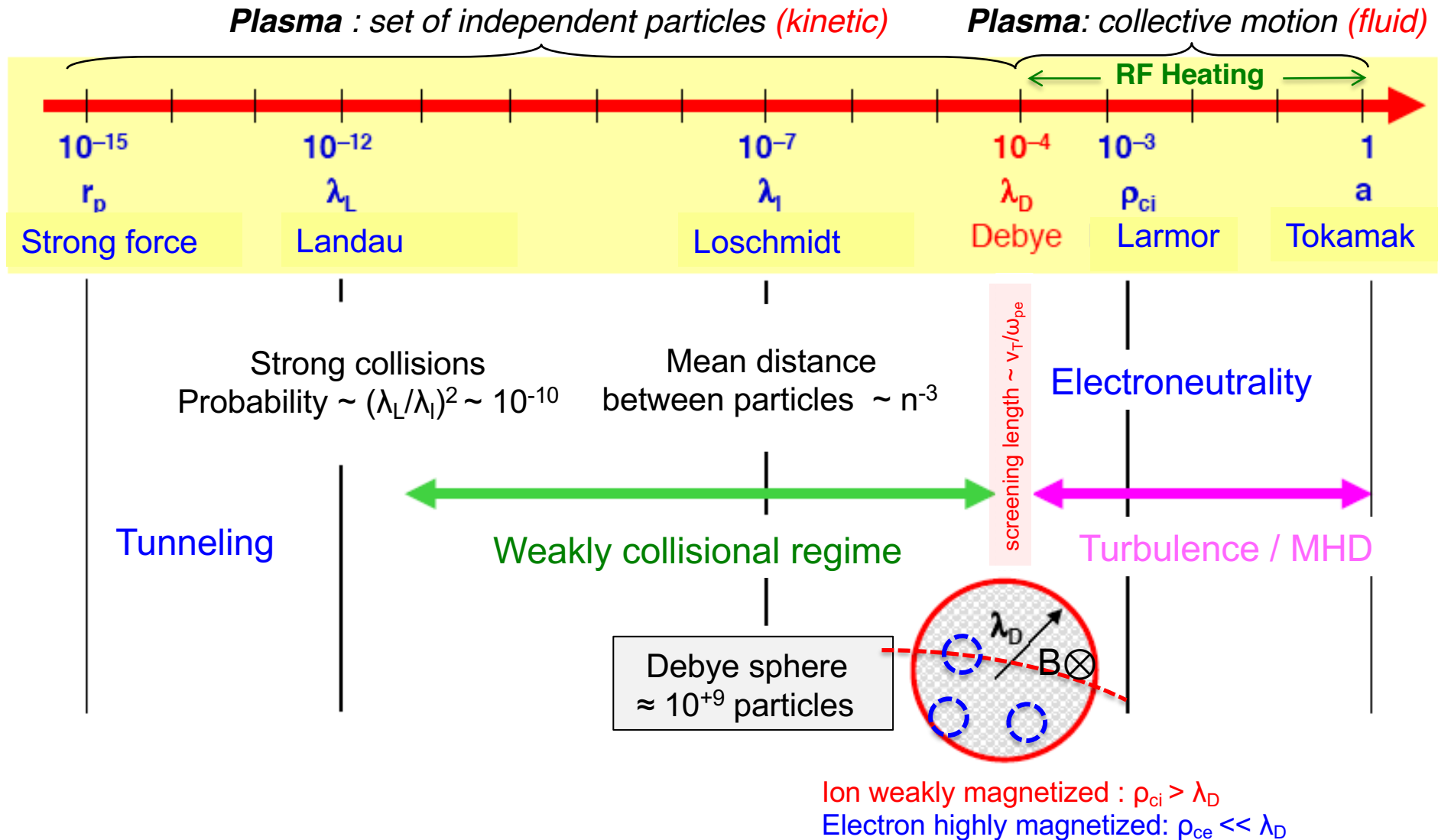
$$\mathbf{P}(\mathbf{x}, t) = \sum_s m_s c^2 \iiint d^3\mathbf{p} (\gamma_s - 1) \partial f_s(\mathbf{x}, \mathbf{p}, t) / \partial t$$

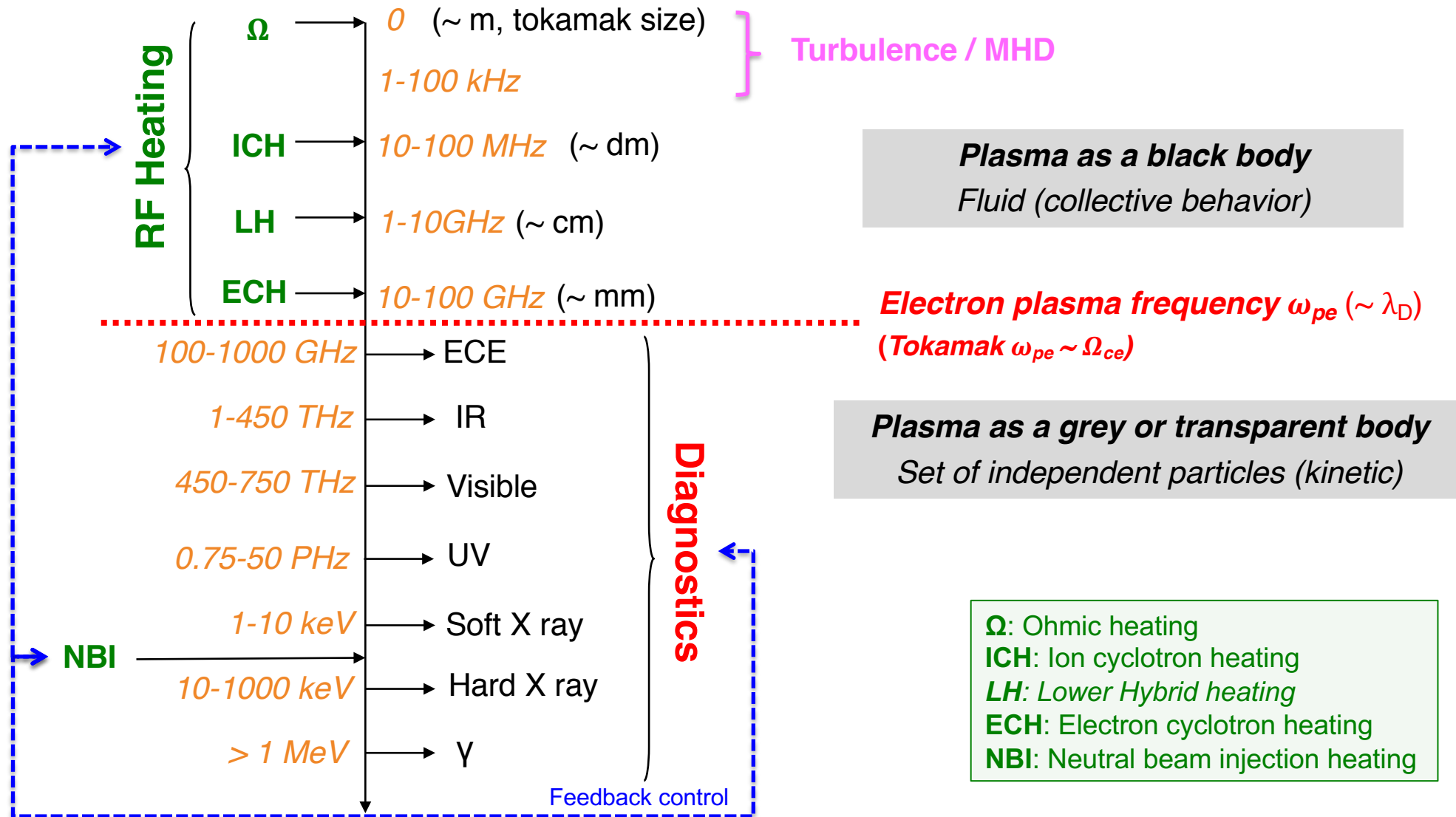
$$\mathbf{J}(\mathbf{x}, t) = |e| \sum_s Z_s \iiint d^3\mathbf{p} f_s(\mathbf{x}, \mathbf{p}, t) \mathbf{p} / \gamma_s$$

Plasma : a 6-D time-dependent problem with multiple scales !

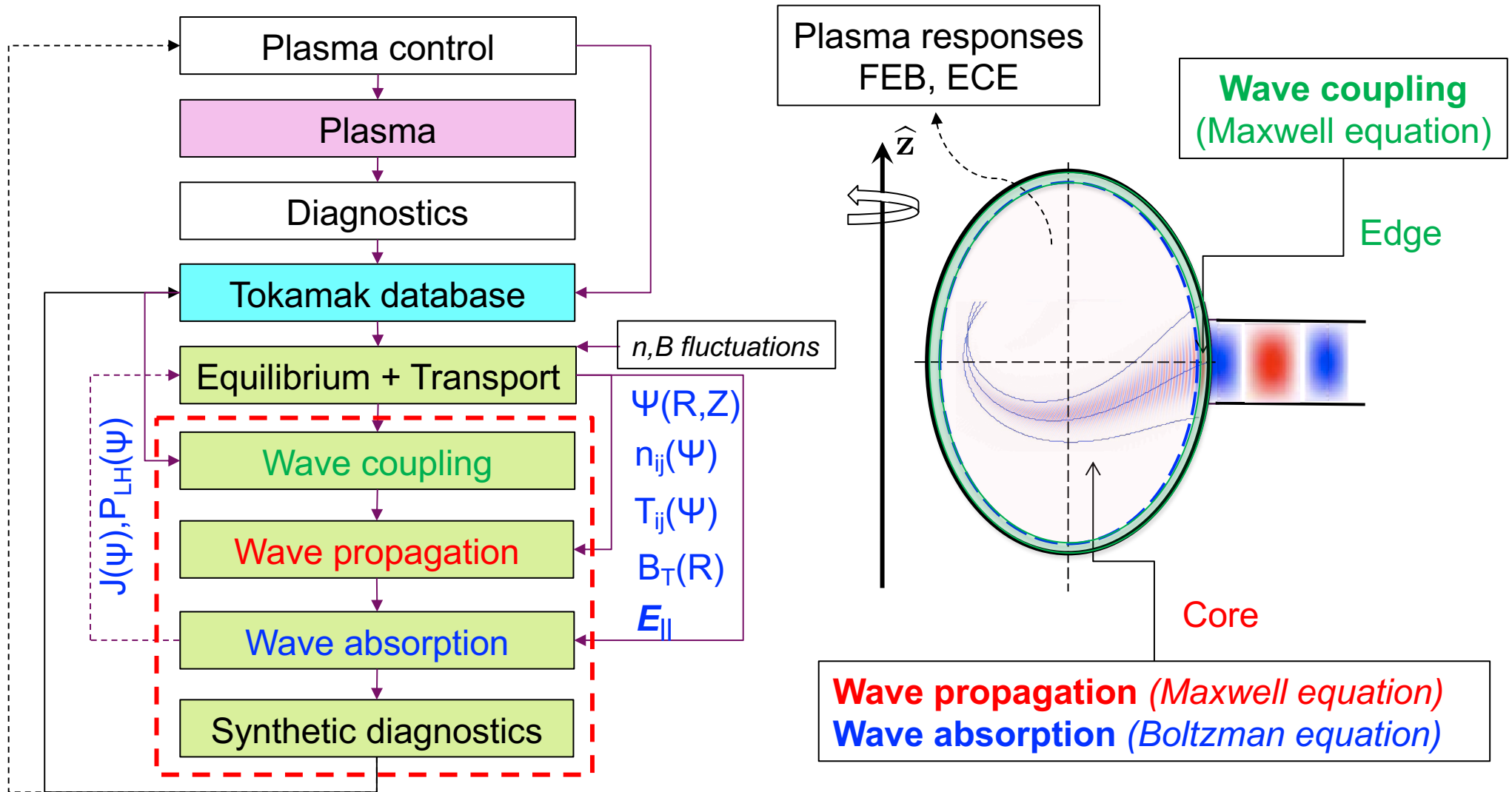
- Recovering microscopic informations from macroscopic measurements (inversion) is an ill-posed problem : an infinity of solutions may explain the observations !
- First principles modeling try to by-pass this difficulty by rebuilding experimental results (synthetic diagnostics) from a set of microscopic physical processes considering assumptions that reflect the multiple scales problem (time/space ordering)
- The uniqueness of the solution provided by first principles modeling is not guaranteed by this procedure. But extensive comparisons between calculations and observations may validate the description within a given parameters space → ***large number of simulations***

- **Microscopic scale** : exact local physical processes in 6-D phase space
- **Mesoscopic scale (kinetic)** : time/space ordering (*code modularity*)
 - Curvilinear metrics
 - Dimension reduction 6-D \rightarrow 1-D (radial) + 2-D (momentum)
Hamiltonian theory (Lie transform), symmetry or local averaging
- **Macroscopic scale (fluid)** : global averaging \rightarrow *diagnostics*
 - Geometry
 - Energy

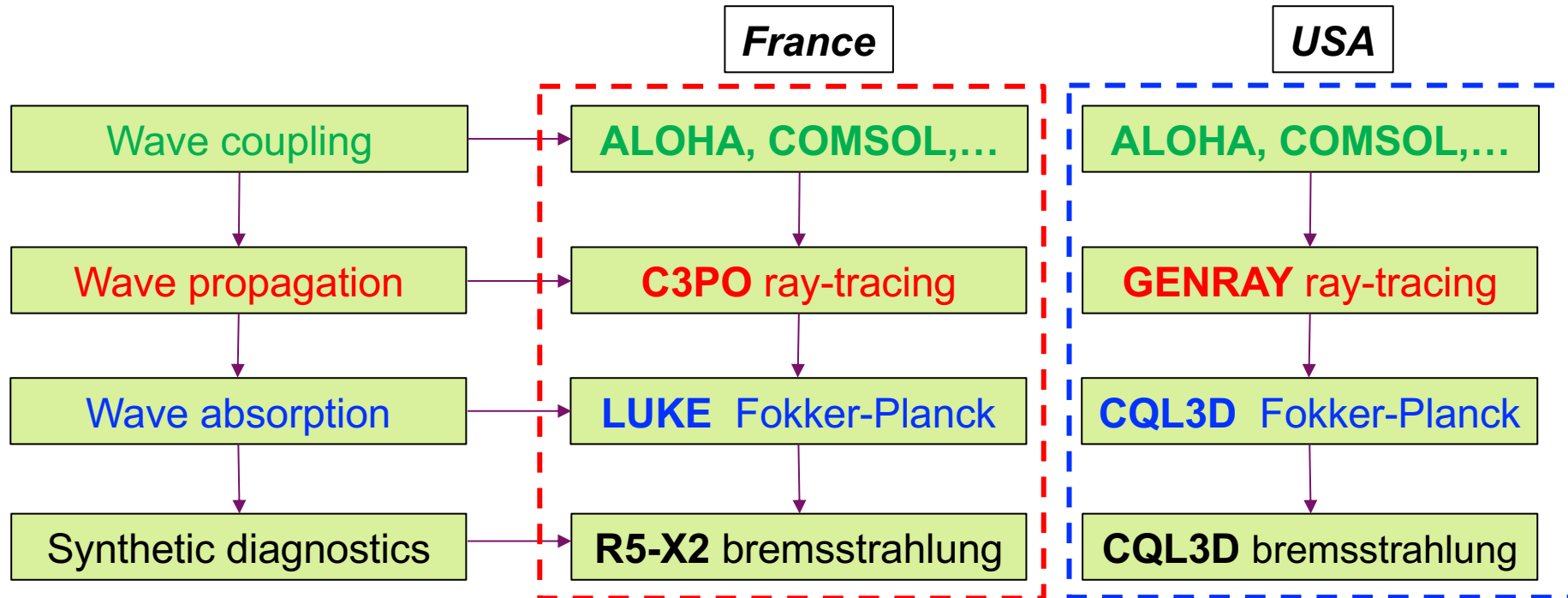




- Fast electrons play an important role in tokamak plasmas for *steady-state operation, MHD stability, plasma heating,...*
- Fast electrons can be driven :
 - by large inductive electric fields → *runaways*
 - by resonant interactions with RF waves → *heating & CD*
- Their dynamics depends of the toroidal MHD equilibrium but also may impact it → *self-consistency*
- Fast electrons dynamics may be also perturbed by plasma fluctuations and MHD activity



Y. Peysson et al., EPJ Web of Conferences, 157 (2017) 02007

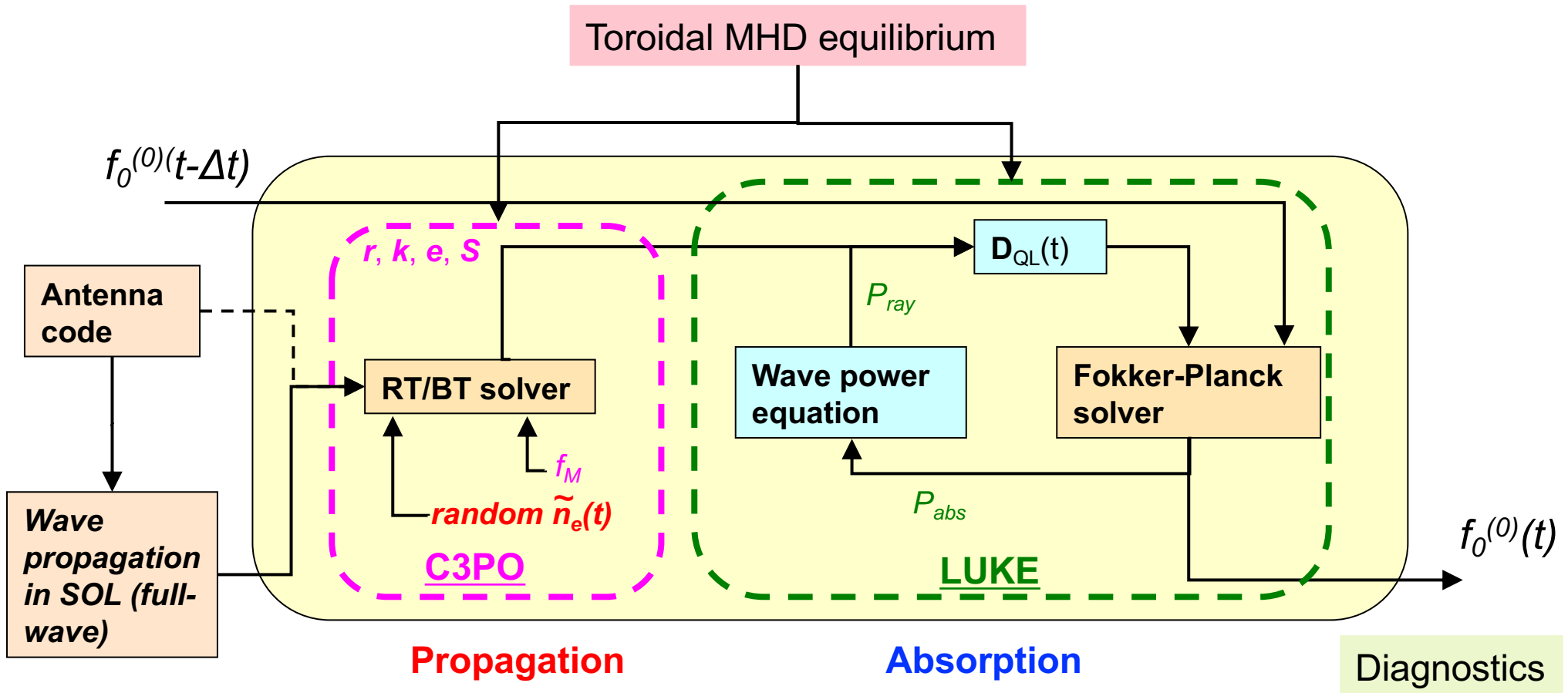


Tore Supra, WEST (France)
 EAST, HL-2A, CFETR (China)
 Alcator C-Mod (US)
 TRIAM-1M (Japan)
 TCV (Switzerland)
 ITER,...

J. Decker and Y. Peysson, EURATOM-CEA report, (2004) EUR-CEA-FC-1736
 Y. Peysson and J. Decker, Fusion Science and Technology, 65 (2014) 22
 Y. Peysson et al., PPCF 54 (2012) 045003
 Y. Peysson. and J. Decker, Phys. Plasmas,15 (2008) 092509

A.P. Smirnov and R. W. Harvey, Report CompX-2000-01 (2003)
 R.W. Harvey and M.G. McCoy, IAEA Conf. Proc. (1992) 489

Y. Peysson et al., EPJ Web of Conferences, 157 (2017) 02007



Weak damping approximation → code modularity

- Curvilinear coordinate system: $(\rho(\psi), \theta, \phi)$
- 2-D axisymmetric configuration (cylinder, dipole, torus) + 3-D perturbation (nested magnetic flux surfaces)
- Vectorization of the magnetic equilibrium: Fourier series + piecewise cubic interpolation using Hermite polynomials: no interpolation performed at each time step
- **(4,5) order Runge-Kutta**
- **Rays are calculated inside the separatrix.** Specular reflexion enforced - if needed - at $\rho=1$.
- Rays calculations are almost stopped when the rf power is linearly damped
- **Cold, warm, hot and relativistic dielectric tensors**
- **Non-resonant collisional absorption** (for very cold plasmas)
- Written in C (MatLab mex-file)

Y. Peysson et al., PPCF 54 (2012) 045003

Separation between **plasma dispersion models** and the metric associated to the magnetic equilibrium

$$\frac{\partial X_{ij}^s}{\partial \mathbf{Y}} = \frac{\partial X_{ij}^s}{\partial n_{\perp}} \frac{\partial n_{\perp}}{\partial \mathbf{Y}} + \frac{\partial X_{ij}^s}{\partial n_{\parallel}} \frac{\partial n_{\parallel}}{\partial \mathbf{Y}} + \frac{\partial X_{ij}^s}{\partial \beta_{T_s}} \frac{\partial \beta_{T_s}}{\partial \mathbf{Y}} + \frac{\partial X_{ij}^s}{\partial \bar{\omega}_{ps}} \frac{\partial \bar{\omega}_{ps}}{\partial \mathbf{Y}} + \frac{\partial X_{ij}^s}{\partial \bar{\Omega}_s} \frac{\partial \bar{\Omega}_s}{\partial \mathbf{Y}}$$

$$\mathbf{Y} = (\mathbf{X}, \mathbf{k}, t, \omega)$$

$$\beta_s = \sqrt{kT_s / m_s c^2}$$

$$\bar{\omega}_{ps} = \omega_{ps} / \omega \quad \bar{\Omega}_s = \Omega_s / \omega$$

- Linearized relativistic collision operator **with partial screening (for W)**
- Kennel-Engelman-Lerche relativistic rf diffusion operator
- Runaway electron physics with **avalanches and ALD effect**
- Curvilinear coordinate system (ψ, θ, ϕ)
- 2-D axisymmetric configuration (cylinder, torus, dipole)
- 3-D perturbation (nested magnetic flux surfaces)
- Non-uniform grids (f and fluxes)
- Fully implicit or Crank-Nicholson time schemes
- Chang & Cooper interpolation for non-uniform p grid (f_M) and linear interpolation for radial and pitch-angle grids
- Discrete cross-derivatives consistent with boundary conditions (*stable scheme for $D_{qI} \gg 1$*)
- Written in MatLab
- Generalized incomplete LU factorization technique for an arbitrary number of non-zero diagonals (*highly sparse L and U matrices, low memory consumption*). External iterative solvers **MUMPS**,...

- Fully 3-D conservative formulation

Magnetic ripple losses
Runaway electron avalanches

$$\partial f^{(0)} / \partial t + \nabla \cdot \mathbf{S}^{(0)} = s_+^{(0)} - \boxed{s_-^{(0)}}$$

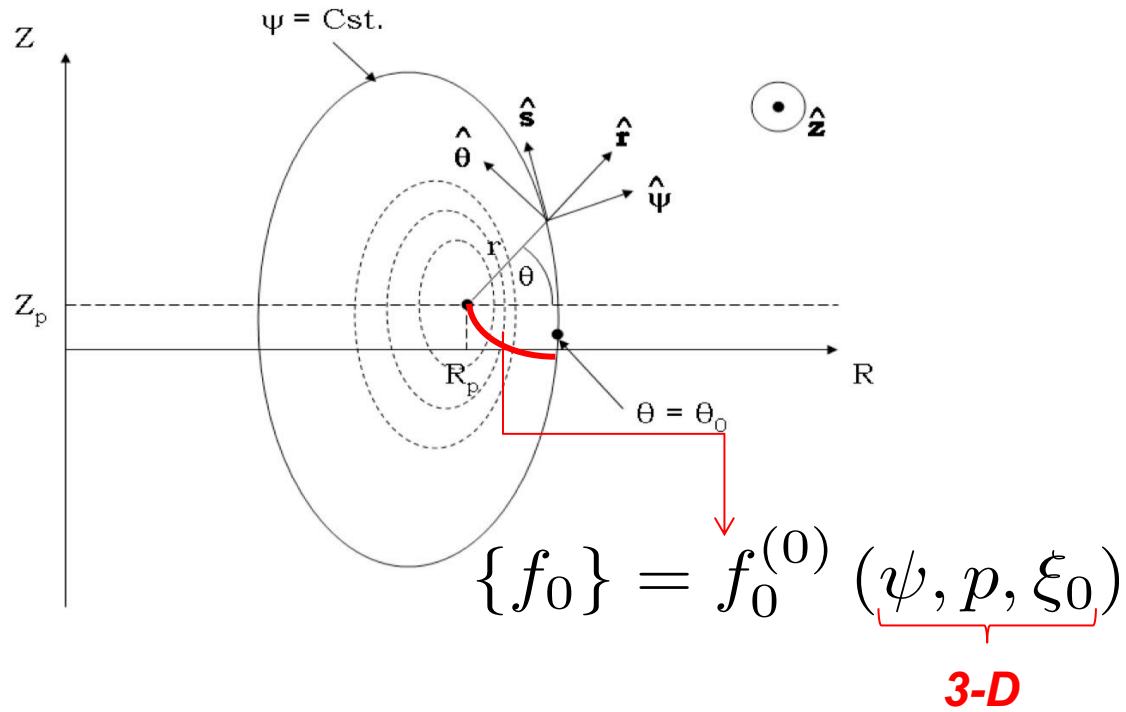
$$\nabla \cdot \mathbf{S}^{(0)} = \frac{B_0}{\tilde{q}\lambda} \frac{\partial}{\partial \psi} \left(\frac{\tilde{q}\lambda}{B_0} \|\nabla \psi\| S_\psi^{(0)} \right) + \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 S_p^{(0)} \right) - \frac{1}{\lambda p} \frac{\partial}{\partial \xi_0} \left(\lambda \sqrt{1 - \xi_0^2} S_\xi^{(0)} \right)$$

configuration space (points to $\tilde{q}\lambda$)

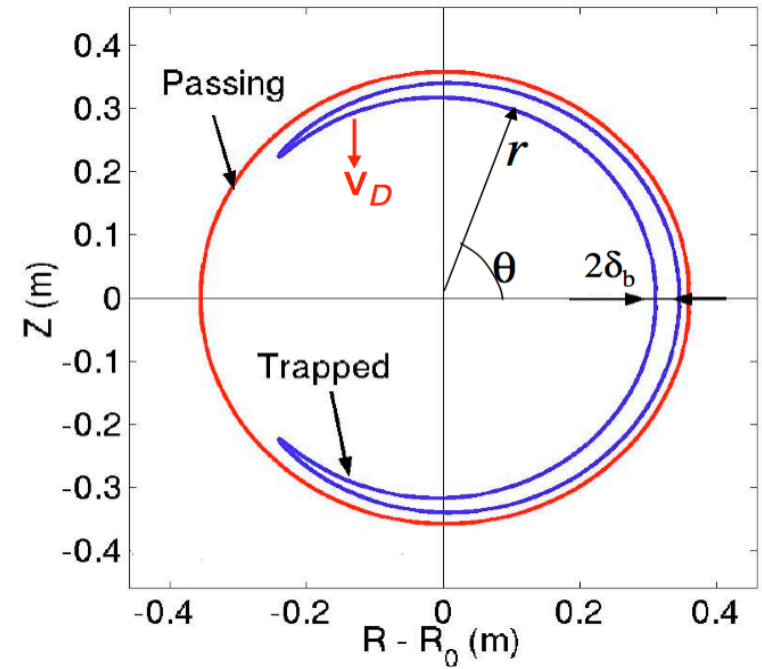
momentum space (points to the second and third terms)

Orbit effect (points to $\lambda \sqrt{1 - \xi_0^2}$)

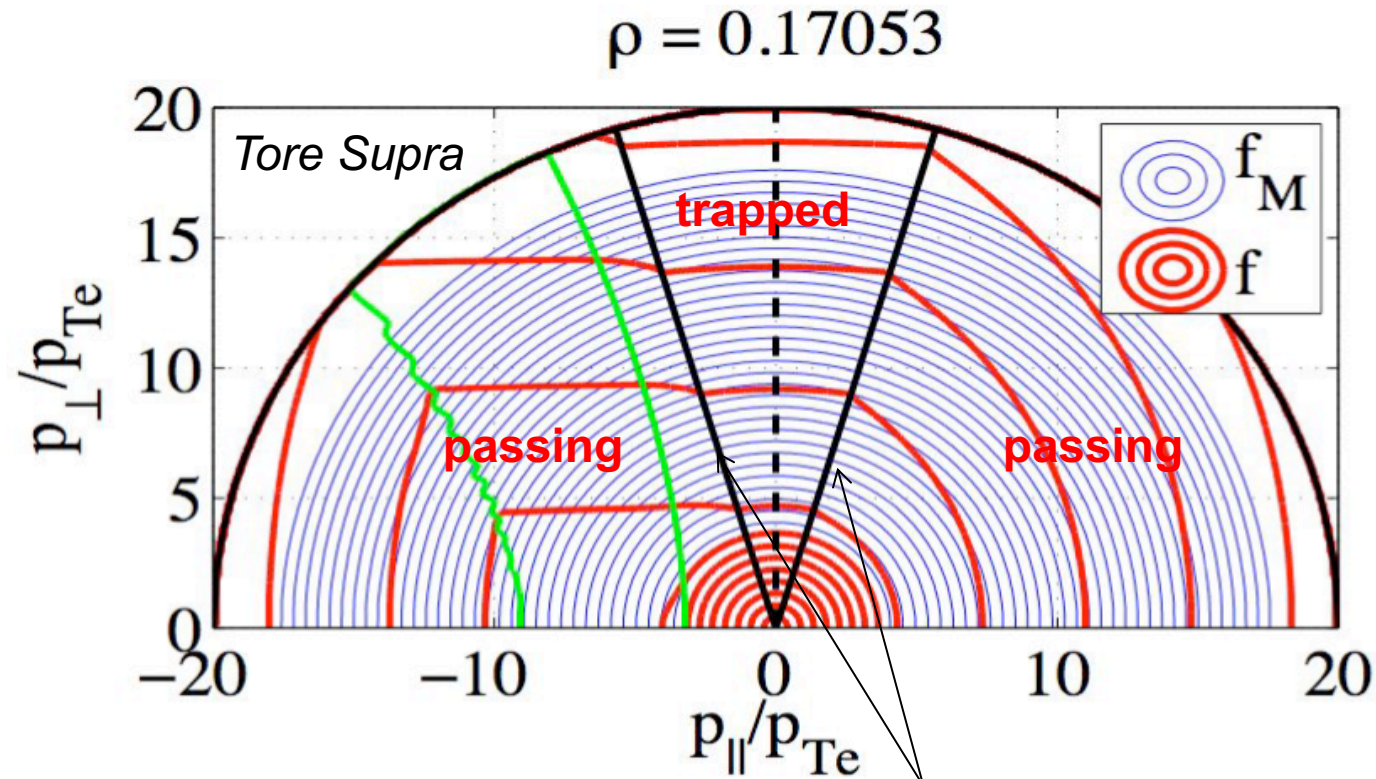
$$\mathbf{S}^{(0)} = -\mathbb{D}^{(0)} \cdot \nabla f^{(0)} + \mathbf{F}^{(0)} f^{(0)}$$



All the electron dynamics is projected at $B = B_{\min}$

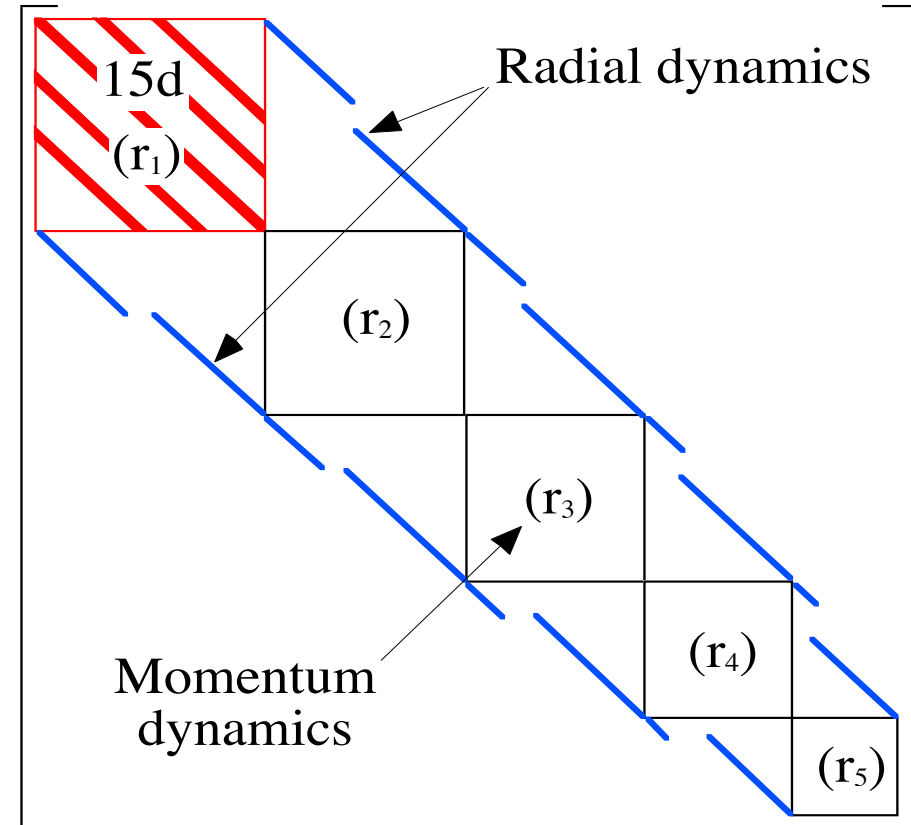
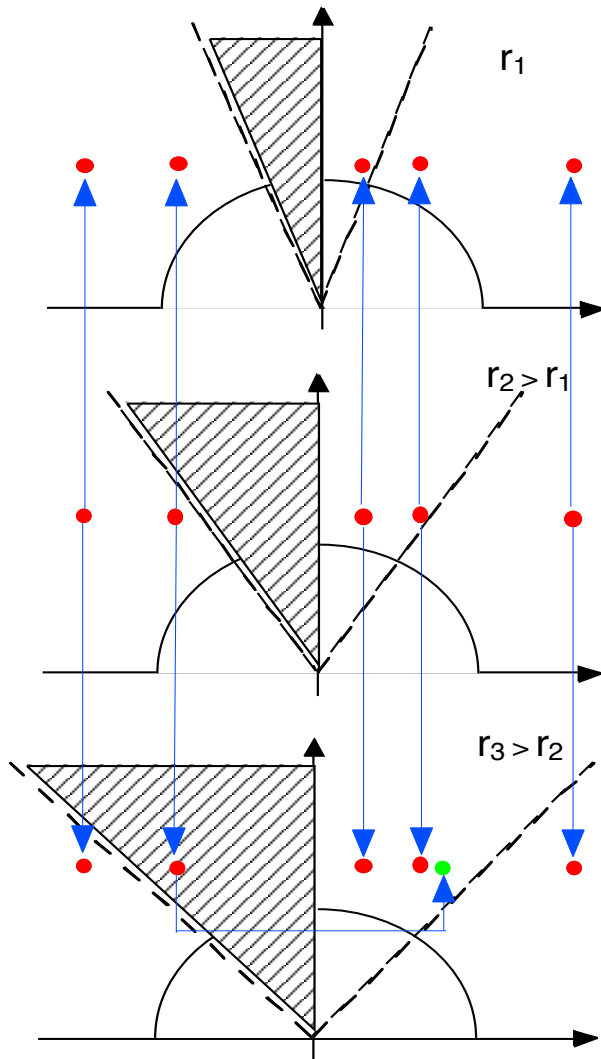


Thin banana width



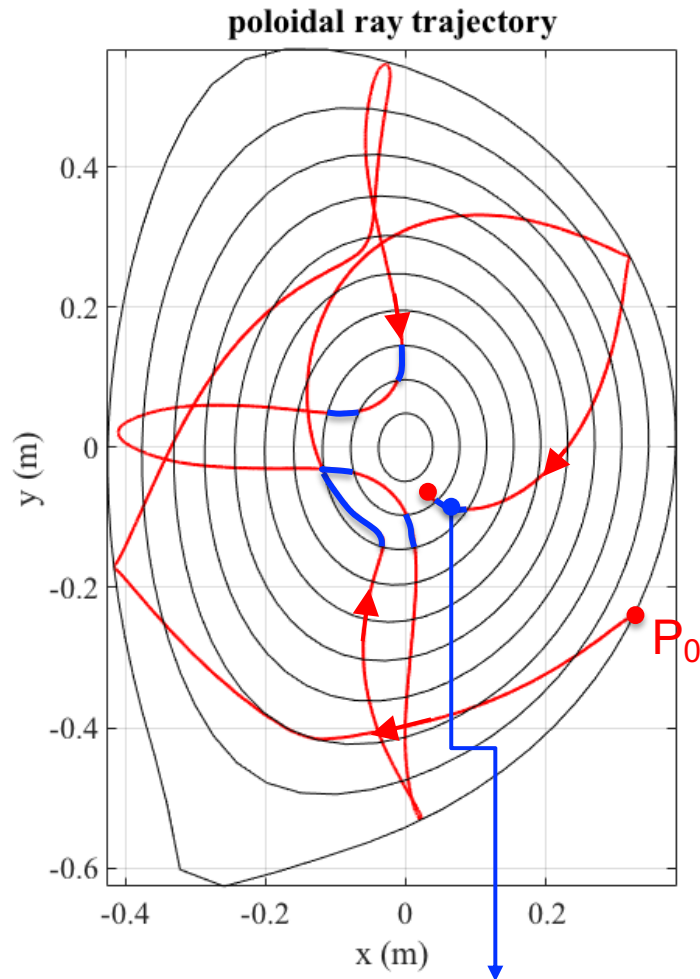
$$\xi_{0T} = \sqrt{1 - \frac{B_{\min}(\psi)}{B_{\max}(\psi)}}$$

Momentum space dynamics on the magnetic flux surface ψ



→ up to $10^{+6} \times 10^{+6}$ entries, highly sparse matrix

Y. Peysson, et al., 15th Top. Conf. on Radio Frequency Power in Plasmas, 2003, vol. 694 of AIP Conf. Proc., pp. 495–498.



Ray fragment in layer at $\psi_{l+1/2}, \theta_b$

- RF power flows almost instantaneously from initial ray position to the last calculated point since

$$v_G / L_{ray} \ll \tau_{bounce} \ll \tau_{coll}$$
- Each ray is split in small fragments depending on the number of plasma layers.

\mathcal{P}_i : RF power carried by the ray fragment i,

$$D_{||}(\psi, p_{||}, p_{\perp}) = \sum_i \frac{\mathcal{P}_i}{\mathcal{P}_{i0}} \frac{D_{||i}}{\sqrt{\pi} \Delta n_{||i}} \exp \left[-\frac{(n_{||i} - n_{||res})^2}{\Delta n_{||i}^2} \right]$$

$n_{||res} = c/v_{||}$: resonance condition at position $(\psi_{l+1/2}, \theta_b)$

$$Q_{LH}(f) = \frac{\partial}{\partial p_{||}} D_{||} \frac{\partial f}{\partial p_{||}} : \text{RF diffusion operator}$$

$$\frac{\partial f}{\partial t} = C(f) + Q_{LH}(f) + \dots : \text{Fokker-Planck equation}$$

Deposited power for fragment i :
$$P_{abs}^i(\psi) = D_{||i} \frac{\mathcal{P}_i}{\mathcal{P}_{i0}} \frac{c}{n_{||i}} \left\langle \frac{\partial f}{\partial p_{||}} \Big|_{v_{||}=c/n_{||i}} \right\rangle$$

$$P_{abs} = \sum_i P_{abs}^i \quad P_{abs}(\psi) = \langle (\gamma - 1) mc^2 Q_{LH}(f) \rangle, \quad \gamma = \sqrt{1 + p^2 / (mc)^2}$$

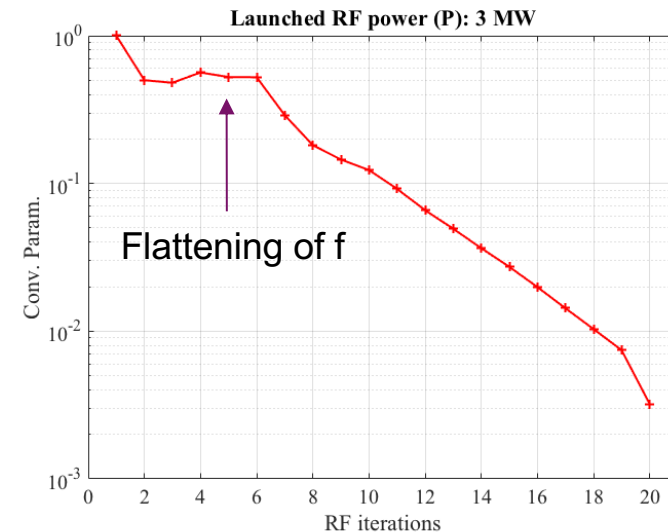
$$\mathcal{P}_i^{new} = P_0 - \sum_{i'=1}^{i'=i} \left(P_{i'}^{NRCA} + P_{abs}^{i'} \right)$$

NRCA: non-resonant collisional absorption

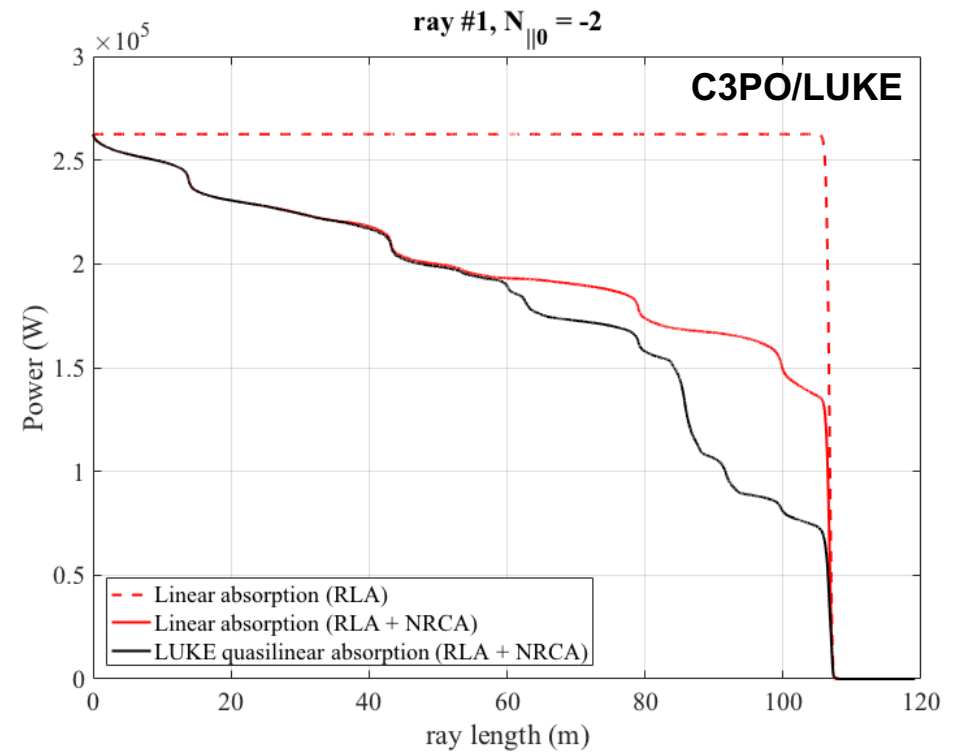
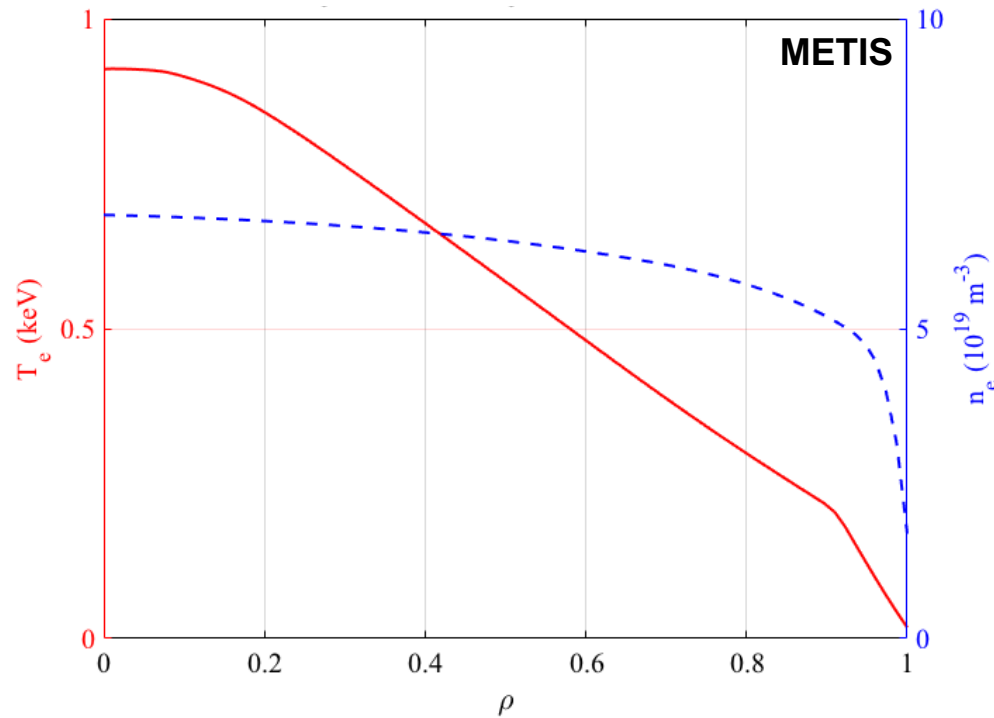
RLA: resonant Landau absorption

Iterations until $|\mathcal{P}_i - \mathcal{P}_i^{new}| / \mathcal{P}_i \leq 10^{-3}$
for each fragment of each ray : **quasilinear self-consistency** → **f and D_{||} are consistent.**

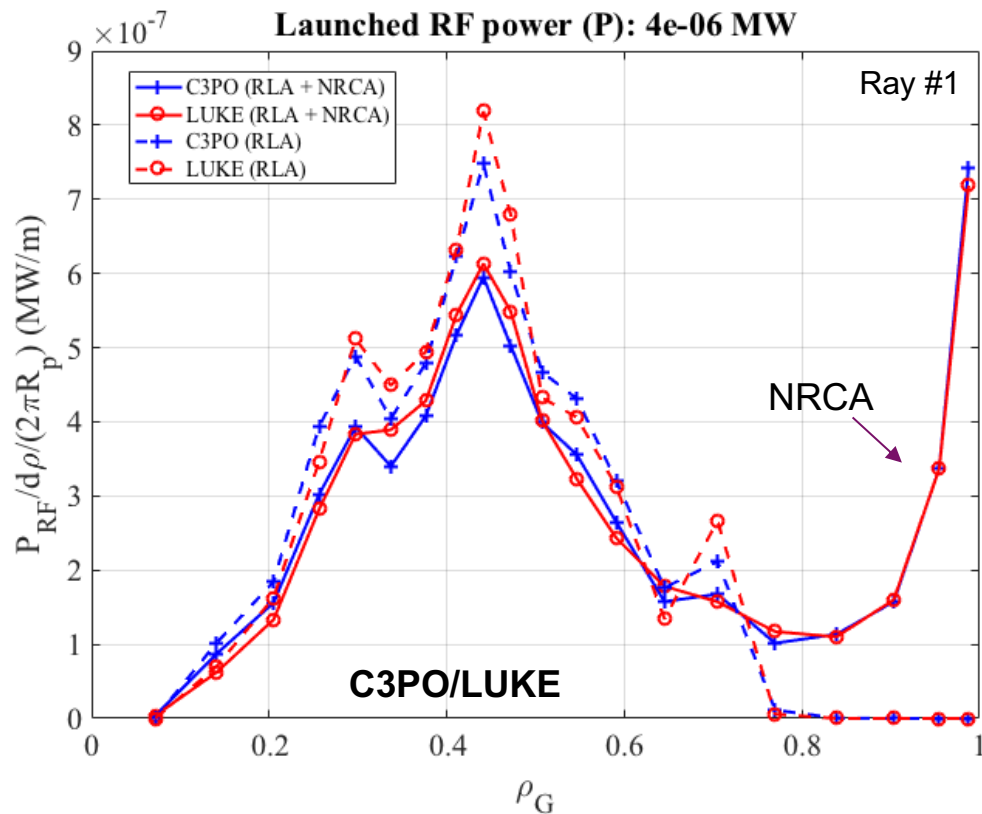
If $\mathcal{P}_i \neq 0$ for the last fragment, the ray is too short and its length must be increased to get full power absorption if possible.



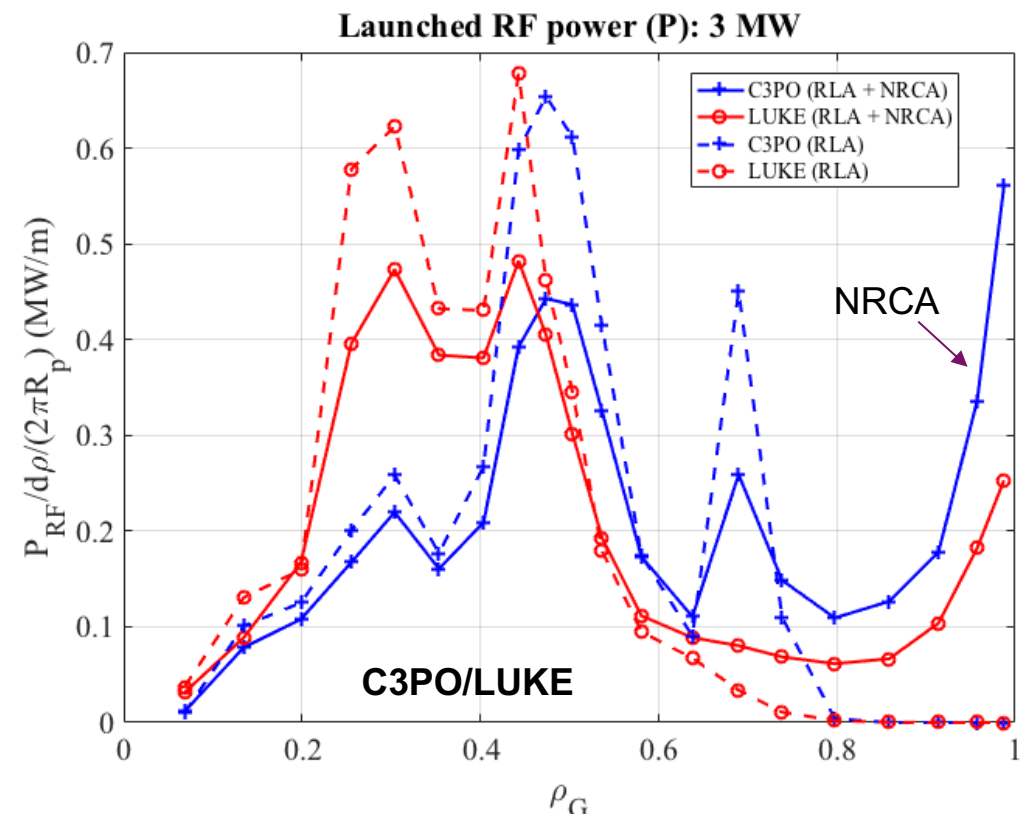
WEST simulation : $\langle T_e \rangle = 0.41$ keV, $\langle n_e \rangle = 5.7 \times 10^{19} \text{m}^{-3}$



Simulation based on a West toroidal MHD equilibrium $\langle T_e \rangle = 0.41$ keV, $\langle n_e \rangle = 5.7 \times 10^{19} \text{m}^{-3}$

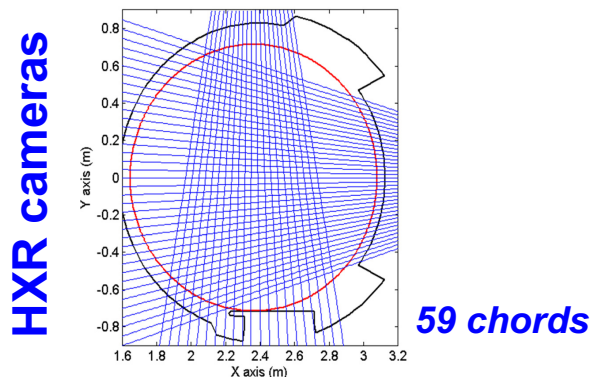


Linear

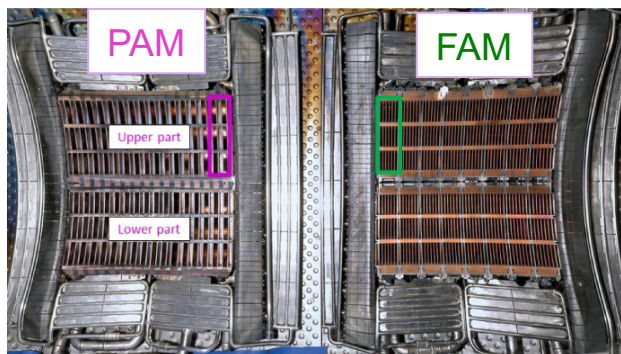


Quasilinear

$R = 2.4 \text{ m}$, $R/a = 3.4$, $B_t < 3.8 \text{ T}$

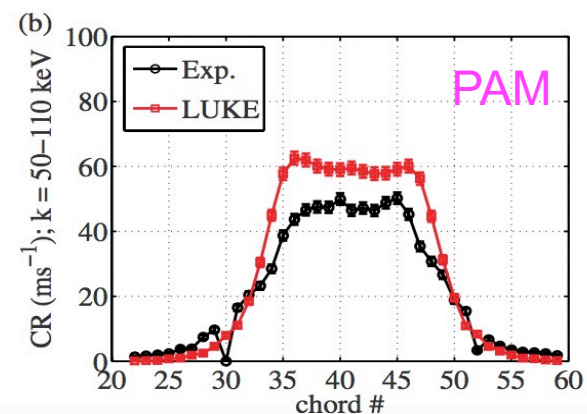
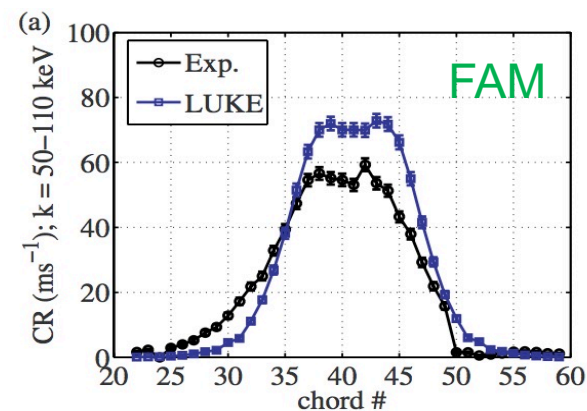


2 LH antennas, multijunction

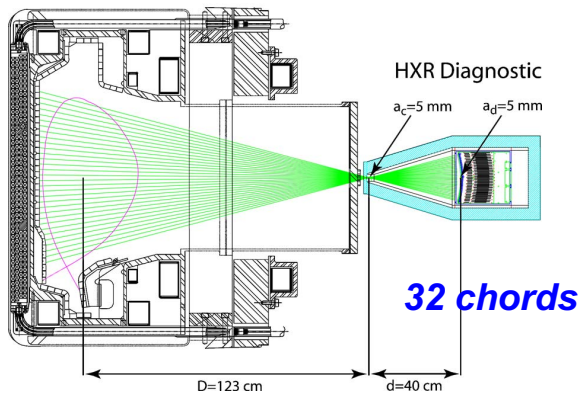


6 rows, 3.7 GHz, 9.2 MW

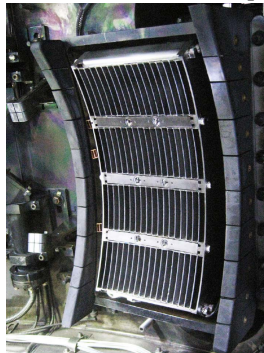
Tore Supra



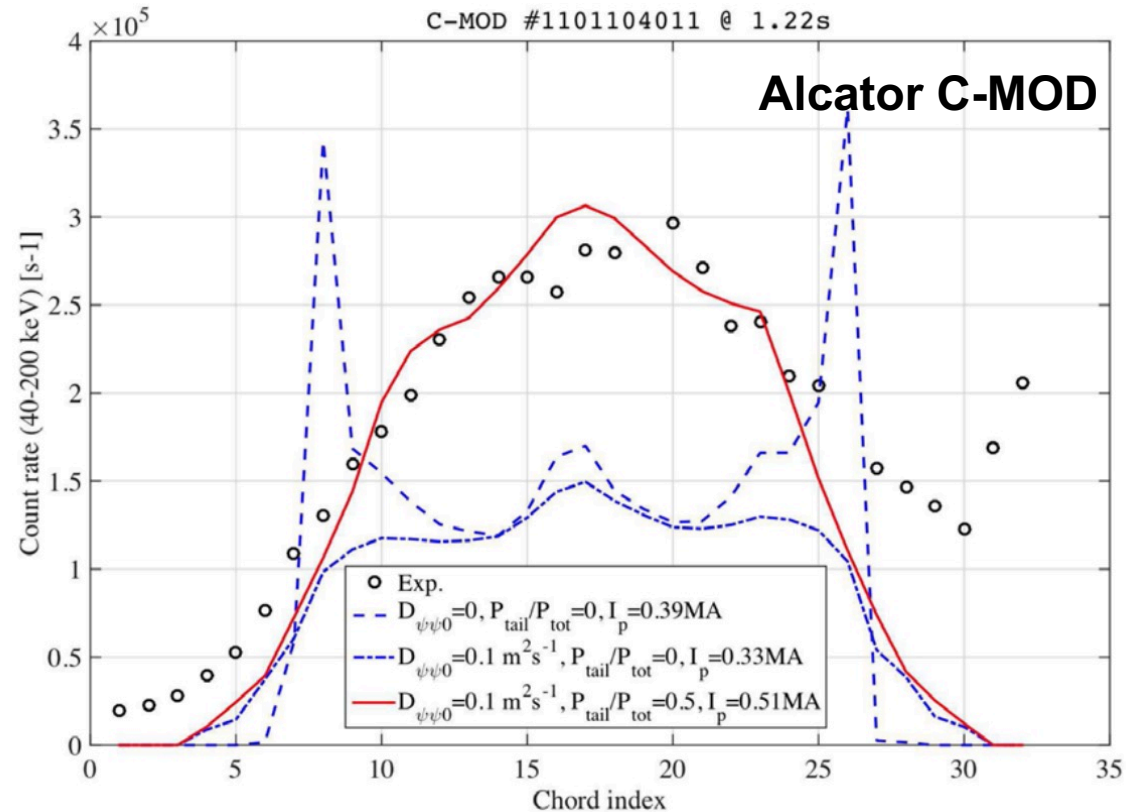
$R = 0.68 \text{ m}$, $R/a = 3.1$, $B_t < 7 \text{ T}$



1 LH antenna, full phasing



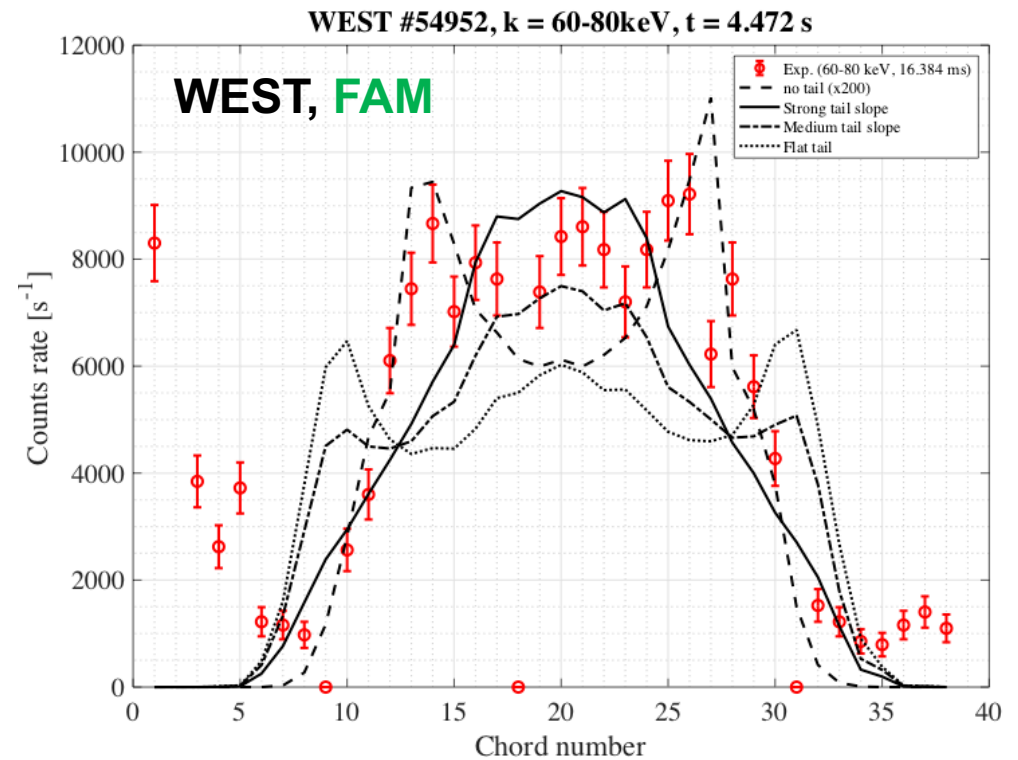
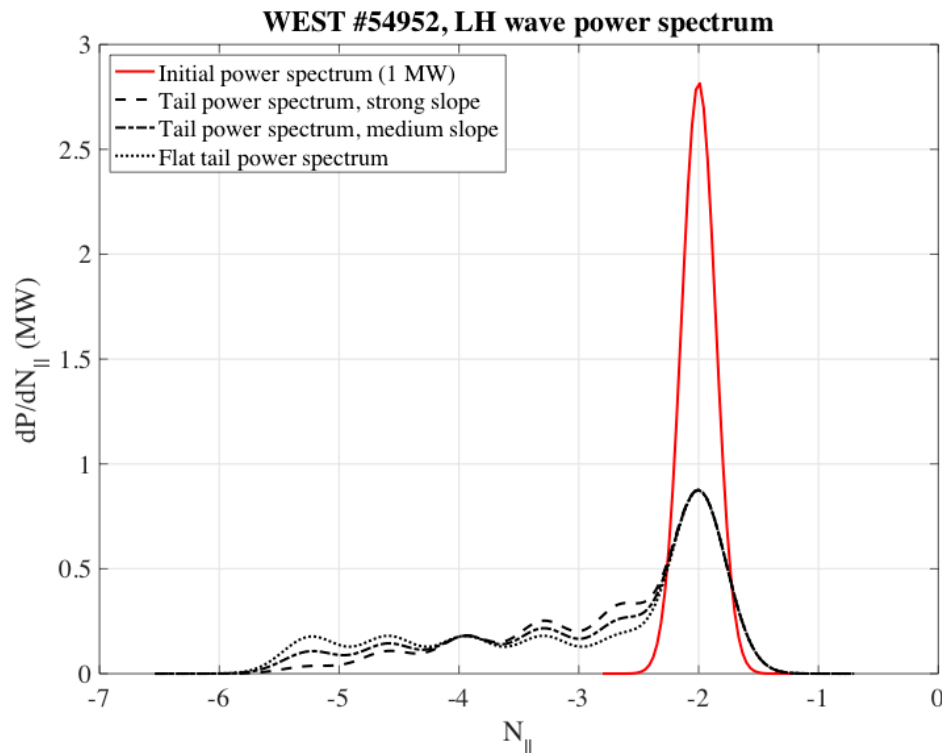
4 rows, 4.6 GHz, 2.5 MW



Liptac, J. et al., Rev. Sci. Instr., 77 (2006) 103504
I. H. Hutchinson et al., Phys. Plasmas, 1 (1994) 1511

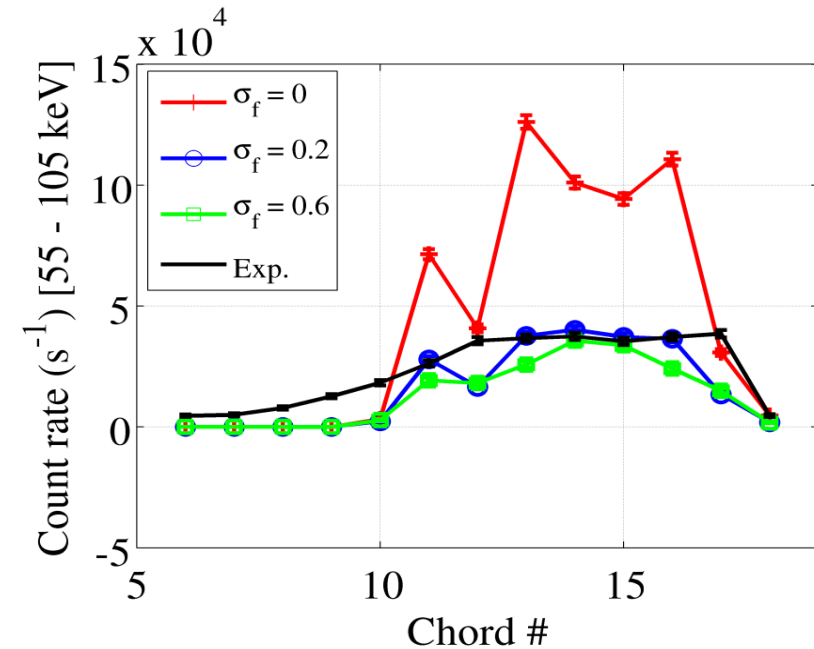
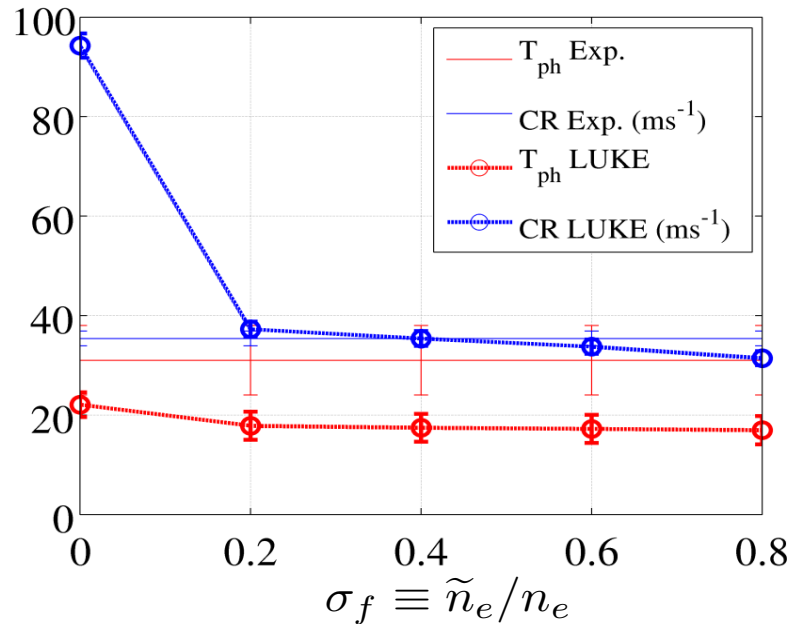
Y. Peysson and J. Decker and E. Nilsson et al., PPCF 58 (2016) 044008

Unbridgeable spectral gap regimes by toroidal refraction : power spectrum should be already broad at the separatrix → **WEST, TRIAM-1M, HL-2A**



Resonance condition : $V_{||} = V_{\phi||} = c/N_{||}$

Peysson, Y, et al. J., Fus. Energy 39 (2020) 270



- **The reconstructed non-thermal bremsstrahlung count rate (central chord) is very close to the experimental HXR signal in the presence of fluctuations** → good match of CR versus chord number for $\sigma_f = 0.2$
- The photon temperature is fairly independent of fluctuations

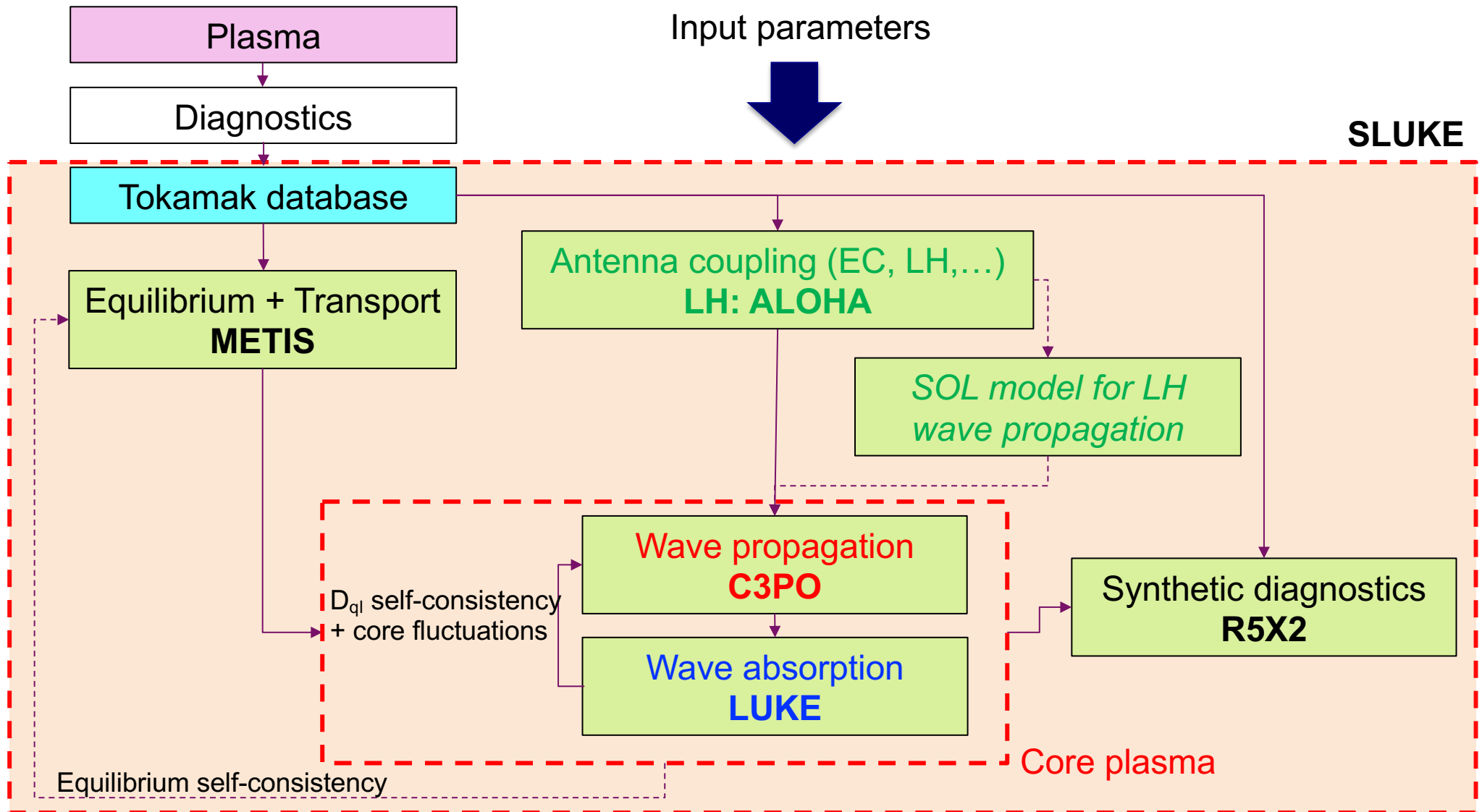
- So far, only “single” shots LUKE simulations have been performed → accurate calculations based on manually validated experimental data, but procedure is long and inappropriate for large multiparametric studies (*extraction of scaling laws, validate model robustness...*)
- **Automatization of the whole chain of codes is mandatory** for multi-machine, multi-shot or multi-time analysis (heterogeneous data)
- **High modularity in the design** when compatible with physics for an easy code maintenance and the possibility to introduce new physics or linking new codes (METIS → RAPTOR, ...)

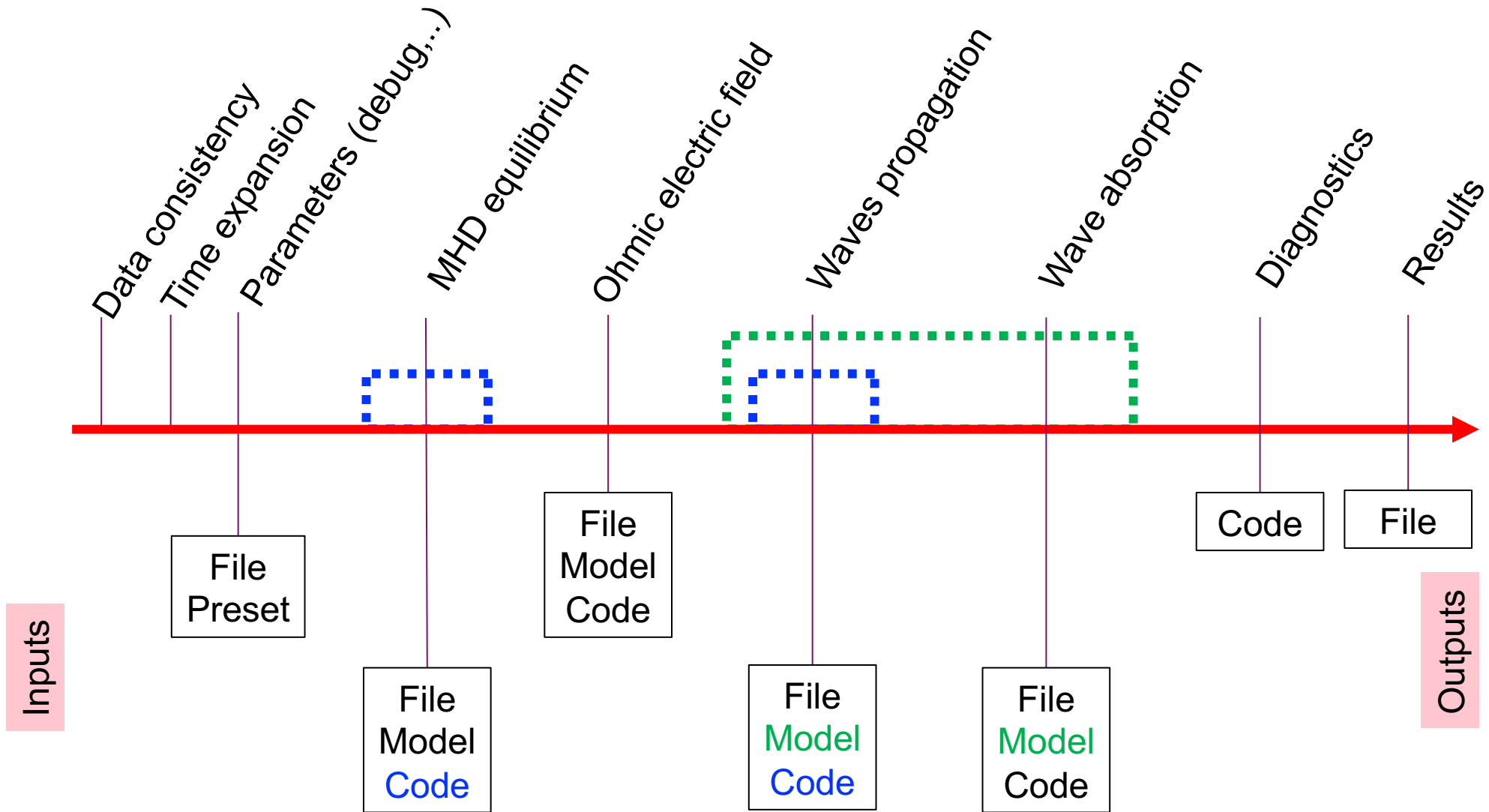
- Each simulation requires large computing and data storage capabilities : calculations may last several hours, memory requirements may exceed several dozen of Megabytes per core and storage data size may reach several Gigabytes per simulation.



- A large number of simulations requires :
 - **Distributed calculations** capabilities with multiple core processors on local and **remote machines**
 - **Fast symmetric ethernet** connections (upload/download)

- The code must be launched by a single call at the top level for an easy symmetric integration : standalone run or integration in another codes
- A single structure of input parameters must be propagated in all SLUKE functions. It should be expressed in text form for easy exchange between users and track errors → control of each calculation everywhere
- Develop a basic object-oriented-like language → easy manipulation of all sets of input parameters.
- Transform any local function by a similar one with distributed remote capability with a simple syntax.
- No graphics except for specific debug : the structure of the main script must be consistent with the physics → adding new physics





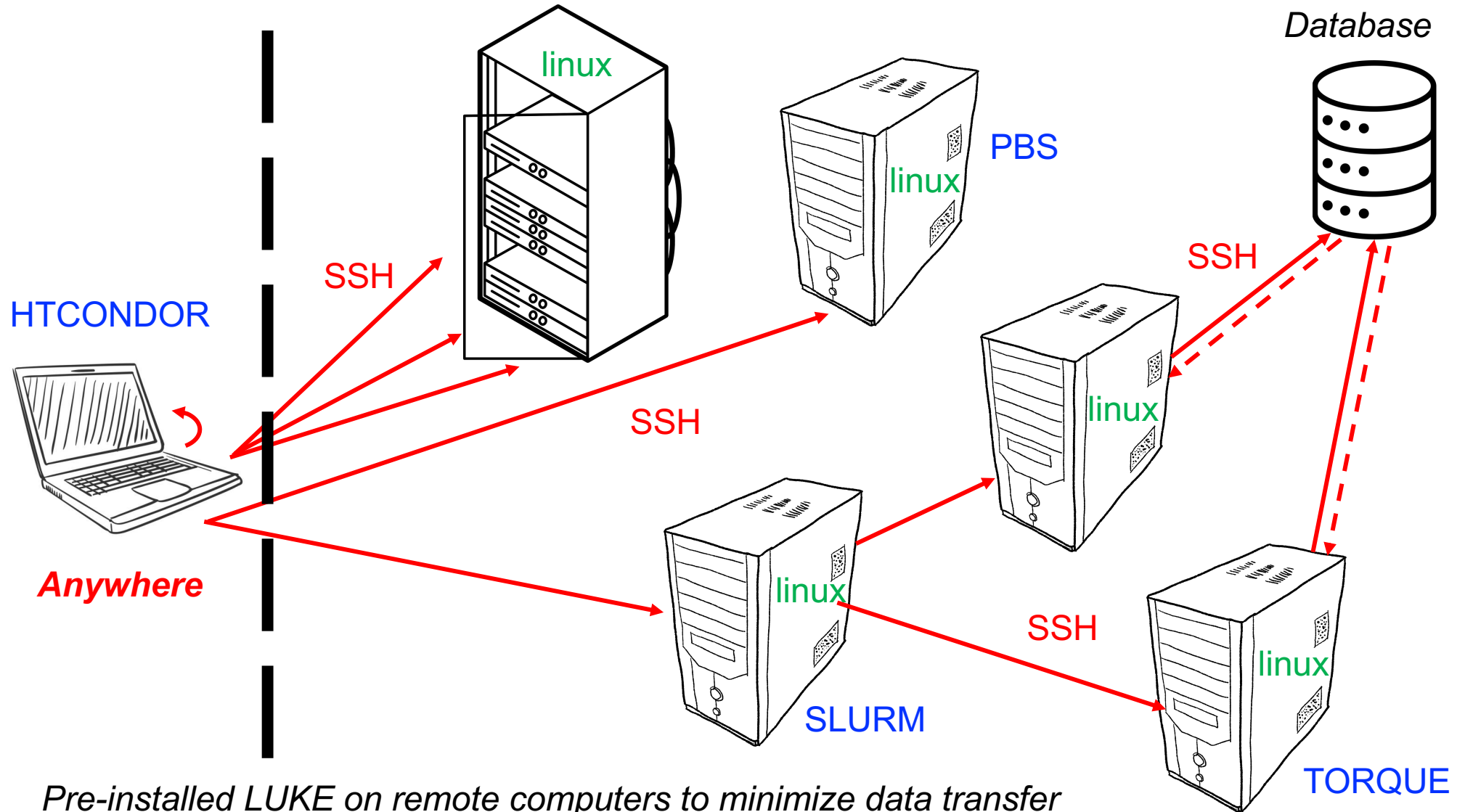
- Enabling distributed and remote computing is one of the most important step towards automatic simulations → done for MatLab functions
- Embedded SSH (SCP) communication protocol + workload manager (PBS, SLURM, TORQUE, HTCONDOR,...)
- A dedicated toolbox has been designed for this purpose with a very simplified syntax :

```
[b1,b2,...] = any_Matlab_function(a1,a2,a3...)
```



```
{[b1,b2,...]} = remotecomputing(@any_Matlab_function,{a1,a2,a3...},2,{a2_range},computer_id)
```

The toolbox may be used for launching non-Matlab codes (Fortran, C, Python scripts, ...)



Pre-installed LUKE on remote computers to minimize data transfer

SLUKE : A single structure for all input parameters in a text script file

```
sparams.machine = {'WEST' 'TS' 'TCV'};
```

Structure of cells for heterogeneous types of inputs

```
%
```

```
%-----
```

```
-----
```

```
%
```

```
sparams.discharge.shot = {'55025' '32299' '11155025'};
```

```
sparams.discharge.tmin = {[3] [8] [9.5]};
```

```
sparams.discharge.tmax = {[3.1] [8.1] [9.9]};
```

```
sparams.discharge.nt = {[1] [1] [4]};
```

Time slice or time intervals

```
%
```

```
%-----
```

```
-----
```

```
%
```

```
sparams.simul.id = {'Ohmic' 'LH flat-top' 'Collapse'};
```

```
sparams.simul.comment = {'' '' ''};
```

```
sparams.simul.enable = {[1] [1] [1]};
```

```
sparams.simul.enforce = {[0] [0] [0]};
```

```
sparams.simul.remote_profile = {[17] [17] [5]};
```

Remote machine ID

```
sparams.simul.wait4results = {[0] [0] [0]};
```

```
sparams.simul.log = {[1] [0] [0]};
```

```
%
```

Toroidal MHD equilibrium

```

sparams.equil.id = {'METIS' 'METIS' 'METIS'};
sparams.equil.comment = {'metis calculation' 'metis calculation' 'metis calculation'};
sparams.equil.source = {'file' 'file' 'file'};
sparams.equil.code = {' ' ' ' '};
sparams.equil.file =
{'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'
'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'
'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'};
sparams.equil.path = {'./INPUTS' './INPUTS' './INPUTS'};

```

Type of data source

Ohmic electric field

```

sparams.ohm.id = {'METIS' 'METIS' 'METIS'};
sparams.ohm.comment = {'metis calculation' 'metis calculation' 'metis calculation'};
sparams.ohm.source = {'file' 'file' 'file'};
sparams.ohm.code = {' ' ' ' '};
sparams.ohm.file =
{'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'
'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'
'55025_8_10_pradok_wok_ddnok_xlh023_dlh052_no_oxig_fne0_run17_new_tung_peak_LUKE.mat'};
sparams.ohm.path = {'./INPUTS' './INPUTS' './INPUTS'};

```

```

sparams.rfwaves.id = {'', 'LHCD', 'LHCD'};%LH wave
sparams.rfwaves.comment = {'', '', ''};
sparams.rfwaves.source = {'', '', ''};
sparams.rfwaves.file = {'', '', ''};
sparams.rfwaves.path = {'', '', ''};
sparams.rfwaves.enable = {'', 1, 1};
%
sparams.rfwaves.antenna.type = {{}, {'LH', 'LH'}, {'LH', 'LH'}};
sparams.rfwaves.antenna.id = {{} {'ne_fixed', 'ne_fixed'} {'ne_optim', 'ne_optim'}};
sparams.rfwaves.antenna.comment = {{} {'', ''} {'', ''}};
sparams.rfwaves.antenna.source = {{}, {'code', 'code'}, {'code', 'code'}};
sparams.rfwaves.antenna.code = {{}, {'ALOHA', 'ALOHA'}, {'ALOHA', 'ALOHA'}};
%
sparams.rfwaves.antenna.LH.ALOHA.port = {{}, {'Q6A', 'Q6B'}, {'Q6A', 'Q6B'}};
sparams.rfwaves.antenna.LH.ALOHA.remote_profile = {{}, {17, 17}, {17, 17}};
sparams.rfwaves.antenna.LH.ALOHA.display.data = {{}, {-1, -1}, {-1, -1}};
sparams.rfwaves.antenna.LH.ALOHA.display.results = {{}, {1, 1}, {1, 1}};
sparams.rfwaves.antenna.LH.ALOHA.optim.method = {{}, {0, 0}, {0, 0}};%(1)
sparams.rfwaves.antenna.LH.ALOHA.optim.ne_guess = {{}, {2.0e17, 2.0e17}, {[0.7e17, 5.0e17], [0.7e17, 5.0e17]}};
sparams.rfwaves.antenna.LH.ALOHA.optim.tolfun = {{}, {1e-2, 1e-2}, {1e-2, 1e-2}};
sparams.rfwaves.antenna.LH.ALOHA.optim.tolx = {{}, {1e-2, 1e-2}, {1e-2, 1e-2}};
sparams.rfwaves.antenna.LH.ALOHA.optim.nitmax = {{}, {10, 10}, {10, 10}};
%

```

Possibility to reload existing simulations

Any antenna code may be considered

Nested sub-structure of cells for handling antenna of different types and numbers

The $N_{||}$ power spectrum is determined with a fixed density in front of the grill

The $N_{||}$ power spectrum is determined by best agreement with measured RC

Easy structure manipulation for user-defined scripts



- *sluke_params_preset* : for preset *sparams* structures (examples, tests)
- *sluke_params_value* : get value of a field of the *sparams* structures
- *sluke_params_script* : generate a text script from a *sparams* structure
- *sluke_params_time* : expand time intervals in a *sparams* structure
- *sluke_params_merge* : group two *sparams* structures in a single one
- *sluke_params_clone* : clone an index of the *sparams* structures
- *sluke_params_consistency* : check the consistency of all fields of a *sparams* structure
- *sluke_params_extract* : extract a substructure in a *sparams* structure
- *sluke_params_modify* : modify fields in a *sparams* structure
- *sluke_params_generator* : user interactive creation of a *sparams* structure
- *sluke_params_defaults* : default *sparams* structures
- *sluke_params_help* : help of *sparams* structure
- ...

```

%
% METIS/ALOHA/C3PO/LUKE/R5X2 simulation of WEST discharge #54802
%
clear all
close all
clc
%
make_sparams_WEST_54802;%load simulation parameters
%
sluke(sparams,mfilename);%main calculations
%
...

```

- May be put in a infinite loop to check simulations which is done and get back all results files. Or done manually. sparams is unchanged for a given set of simulations.
- Partial display may be done as far as simulations are progressively done in the same script. Data exchange by files only.
- Detailed results for a single shot may be displayed using LUKE display tool irunluke_jd.m

```
-----  
SLUKE simulation environment  
Script source : Simulation_54802.m  
6 simulations are considered  
-----
```

Full LUKE simulation is done

```
Simulation #1 [machine : WEST, shot : #54802, tmin : 3.7 (s), tmax : 3.8(s), ID : Ohmic] ...  
---> is completed.   
*****TODO : sluke_hxr 1.176 ***** Development pending
```

```
Simulation #2 [machine : WEST, shot : #54802, tmin : 4.7 (s), tmax : 4.8(s), ID : LH flat-top] ...  
---> ALOHA simulation status (ID:WEST_54802_4.7_4.8_ALOHA_Q6A_ne_2) :  
- job #1 for WEST_54802_4.7_4.8_ALOHA_Q6A_ne_2 is completed.  
- job #2 for WEST_54802_4.7_4.8_ALOHA_Q6A_ne_2 is completed.   
warning: min(zdP) < 0, correcting
```

Antenna calculations are done

```
---> is running.  LUKE simulation is running
```

```
Simulation #3 [machine : WEST, shot : #54802, tmin : 5.6 (s), tmax : 5.7(s), ID : Collapse_1] ...  
---> ALOHA simulation status (ID:WEST_54802_5.6_5.7_ALOHA_Q6A_ne_2) :  
- job #1 for WEST_54802_5.6_5.7_ALOHA_Q6A_ne_2 is completed.   
- job #2 for WEST_54802_5.6_5.7_ALOHA_Q6A_ne_2 is completed.   
warning: min(zdP) < 0, correcting  
---> is running. 
```

ALOHA calculations are done (upper & lower parts)

Simulation #6 after time expansion


```
Simulation #4 [machine : WEST, shot : #54802, tmin : 5.7 (s), tmax : 5.8(s), ID : Collapse_2] ...
---> ALOHA simulation status (ID:WEST_54802_5.7_5.8_ALOHA_Q6A_ne_2) :
- job #1 for WEST_54802_5.7_5.8_ALOHA_Q6A_ne_2 is completed.
- job #2 for WEST_54802_5.7_5.8_ALOHA_Q6A_ne_2 is completed.
warning: min(zdP) < 0, correcting

---> is running.

Simulation #5 [machine : WEST, shot : #54802, tmin : 5.8 (s), tmax : 5.9(s), ID : Collapse_3] ...
---> ALOHA simulation status (ID:WEST_54802_5.8_5.9_ALOHA_Q6A_ne_2) :
- job #1 for WEST_54802_5.8_5.9_ALOHA_Q6A_ne_2 is completed.
- job #2 for WEST_54802_5.8_5.9_ALOHA_Q6A_ne_2 is completed.
warning: min(zdP) < 0, correcting

---> is running.

Simulation #6 [machine : WEST, shot : #54802, tmin : 5.9 (s), tmax : 6(s), ID : Collapse_4] ...
---> ALOHA simulation status (ID:WEST_54802_5.9_6_ALOHA_Q6A_ne_2) :
- job #1 for WEST_54802_5.9_6_ALOHA_Q6A_ne_2 is completed.
- job #2 for WEST_54802_5.9_6_ALOHA_Q6A_ne_2 is completed.
warning: min(zdP) < 0, correcting

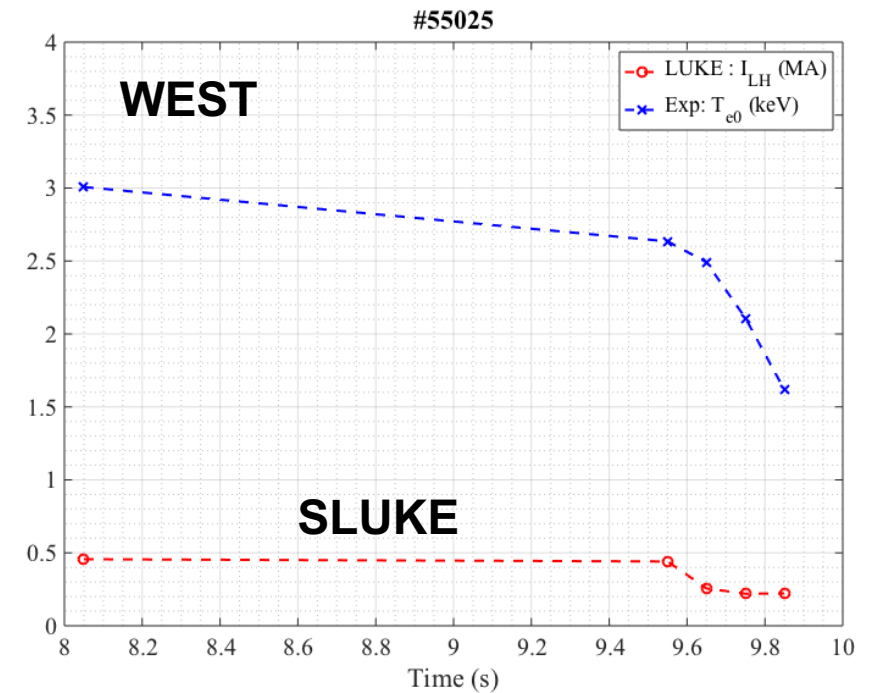
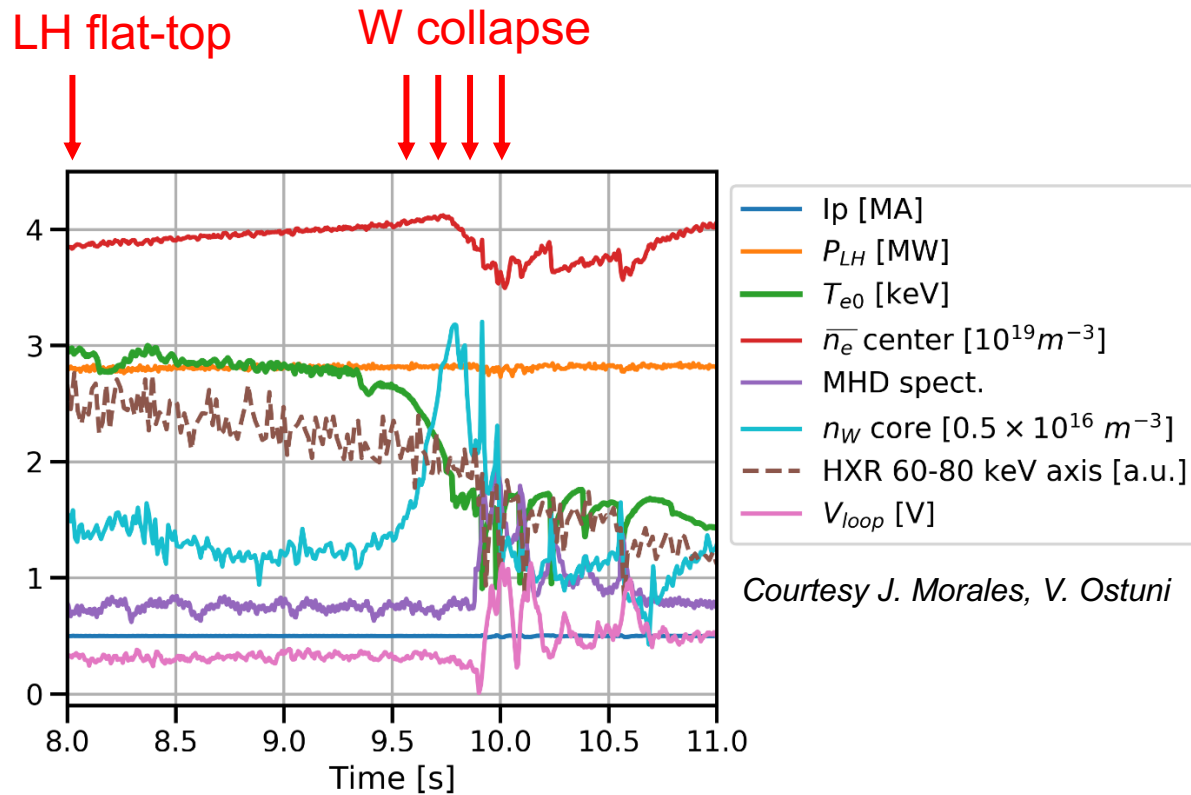
---> is running.
```



Simulation after time expansion

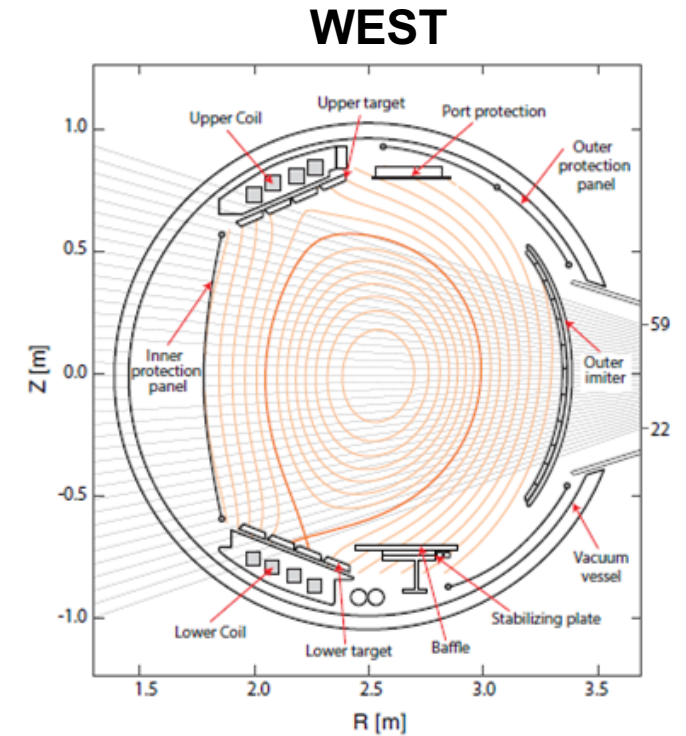
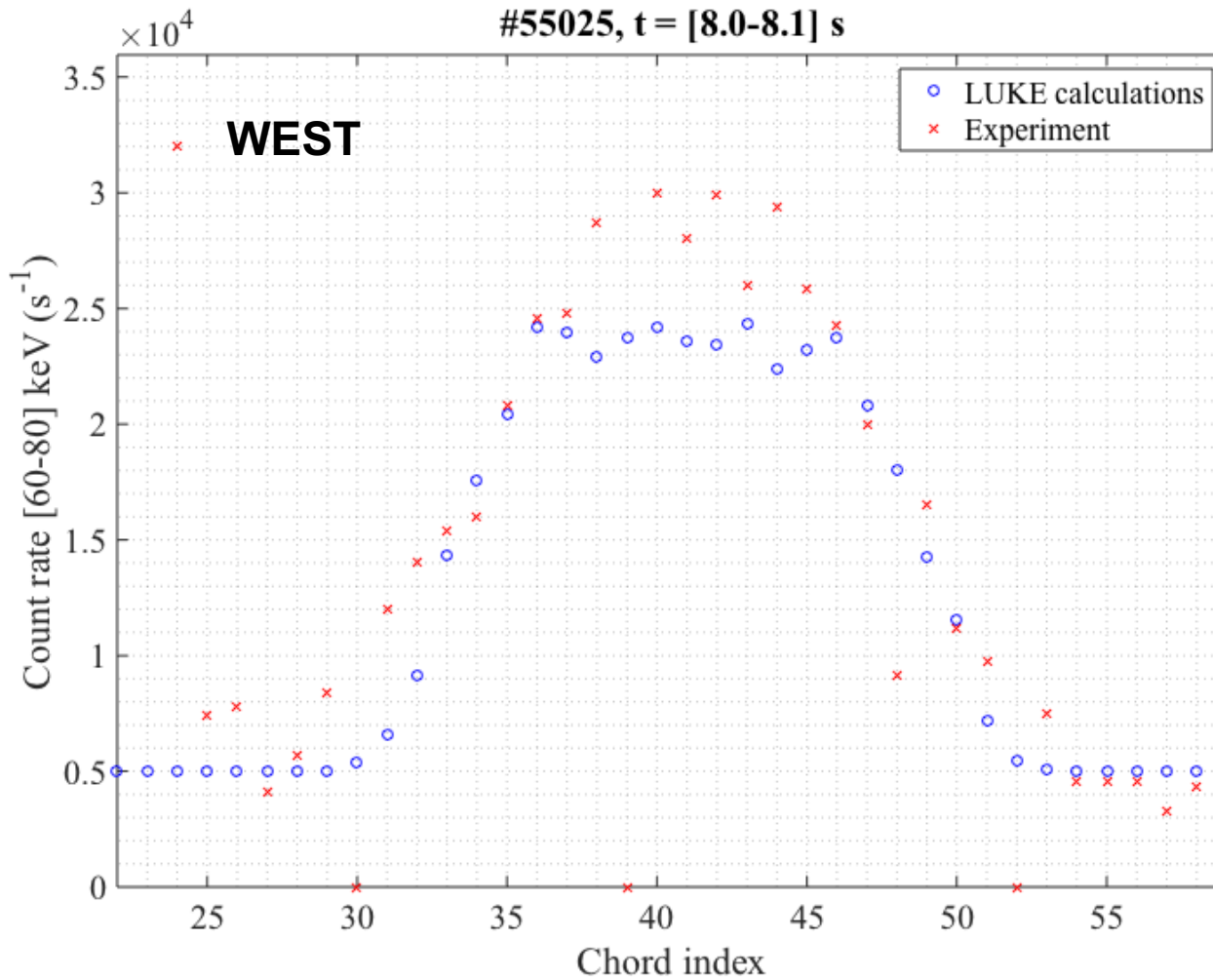
- SLUKE is fully operational
- SLUKE is easy to use and fully customizable → based on MatLab text scripts
- Primarily designed for Tore Supra and WEST yet, but developments for other machines are scheduled.
- Open new capabilities for physics studies with quantitative assessments against experimental observations (if data are available)
 - Long time evolutions (RE dynamics, W collapses, ramp-up, synergies...)
 - Self-consistency between RF driven current with toroidal MHD equilibrium (resistive time)
 - Statistical studies using a large number of experimental results : *multi-time, multi-shot, multi-machine*

SLUKE simulations for 3 time intervals (Ohmic, LH flat-top, W collapse)



All equilibria are from METIS

J. F. Artaud et al., Nucl. Fusion, 58 (2018) 105001



With offset : HXR backscattering by the inner wall ?

- First principles modeling fast electron physics has reached a quite mature level with existing LUKE environment (*ALOHA/METIS/C3PO/LUKE/R5X2*)
- A new framework SLUKE has been developed for large scale quantitative first principles simulations : multi-time, multi-shot and multi-machine, thus allowing new physics studies.
- Further developments will concern LUKE kernel principally → LUKE 2 : finite banana width effects (*RF wave induced transport, self-consistent bootstrap current for non-Maxwellian distribution,...*) (theory is already done) and self-consistent interactions between fast electrons and MHD modes (*principally for RE physics*)
- New synthetic diagnostics will be added to SLUKE framework.